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EXHIBIT 2

Satellite Tool Kit
Astrogator

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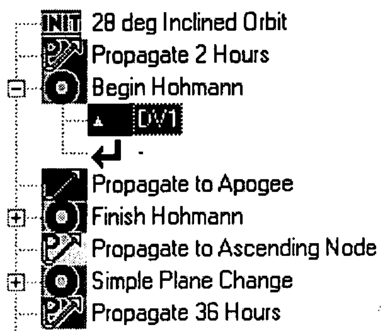
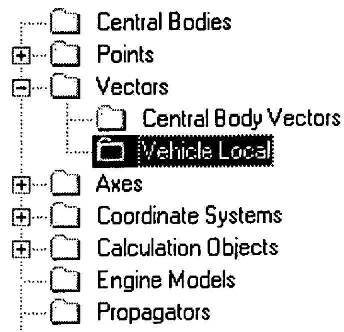
WELCOME TO ASTROGATOR!

Mission Control Sequence



Astrogator Browser



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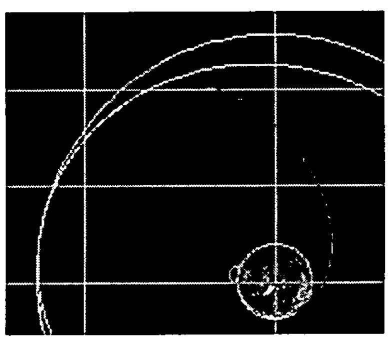
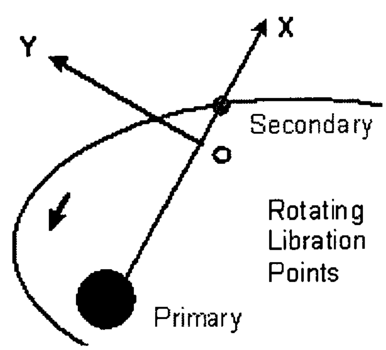


Equations & Constants



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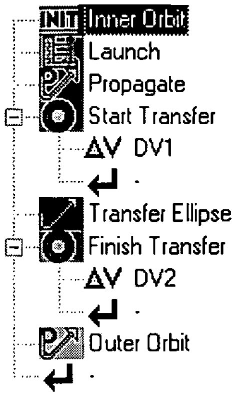
MISSION CONTROL SEQUENCE



The Mission Control Sequence (MCS) is the core of your space mission scenario. By adding, removing, rearranging and editing MCS Segments, you can define a mission of any desired level of complexity. The MCS is represented schematically by a tree structure appearing in the left pane of the Orbit tab of the Satellite Basic Properties window, such as the simple Hohmann Transfer shown here. The MCS tree mirrors the timeline of events constituting your space mission.

Click here for further information on:

MCS segments

Editing the MCS tree

Running the MCS

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Initial State | Spacecraft Configuration | Update Segment

Initial State & Spacecraft Configuration

The Initial State segment provides a means of defining the orbital elements and physical values of a spacecraft at any given point in the space mission scenario. It is usually the first segment in the Mission Control Sequence. In addition, there is an Update segment that allows changes in the spacecraft's physical values to be noted. Both of these segments can be accessed as part of the MCS or from the Astrogator Component Browser.

Initial State Segment

In the Initial State segment, you can select a coordinate system, enter orbital elements of several different types and configure the spacecraft's physical values.

Selecting a Coordinate System

The name of the currently selected coordinate system is displayed in a read-only field. To select a different coordinate system, click the Change... button to the right of this field and make the desired selection in the window that appears. The name of that coordinate system will then appear in the Coordinate System field.

Entering Orbit Elements

The Initial State segment lets you select from among the following Element Types:

Type	Description
Cartesian	Specifying an orbit by three position elements and three velocity elements in a rectangular coordinate system.
Keplerian	The classical system, specifying an orbit by six elements describing its size, shape and three-dimensional orientation in space.
Modified Keplerian	A modification of the classical system, using radius of periapsis instead of semimajor axis. Recommended for very elliptic or hyperbolic orbits.
Spherical	A system in which positions are specified as a radial distance from the origin and two angles relative to a fundamental plane.
Target Vector Incoming Asymptote	Used for hyperbolic arrival trajectories.
Target Vector Outgoing Asymptote	Used for hyperbolic departure trajectories.

The elements of each type are described below. For each type, in addition to entering the appropriate elements, enter the Orbit Epoch in the scenario time and date format.

Cartesian Elements

If you select Cartesian as the Element Type, the following six components need to be specified:

Element	Description
X Component	The X component of the spacecraft position vector. Enter a value in the scenario distance unit (e.g. km).
Y Component	The Y component of the spacecraft position vector. Enter a value in the scenario distance unit (e.g. km).
Z Component	The Z component of the spacecraft position vector. Enter a value in the scenario distance unit (e.g. km).
Vx Component	The X component of the spacecraft velocity vector. Enter a value in the scenario distance unit per scenario time unit (e.g. km/sec).
Vy Component	The Y component of the spacecraft velocity vector. Enter a value in the scenario distance unit per scenario time unit (e.g. km/sec).
Vz Component	The Z component of the spacecraft velocity vector. Enter a value in the scenario distance unit per scenario time unit (e.g. km/sec).

Keplerian Elements

If you select Keplerian as the Element Type, the following six components need to be specified:

Element	Description
Semimajor Axis	Half the length of the major (longest) axis of the orbital ellipse. Enter a value in the scenario distance unit (e.g. km).
Eccentricity	The ratio of the distance between the foci to the major axis of the orbital ellipse. Dimensionless.
Inclination	The angle from the +Z axis of the coordinate system to the angular momentum vector of the spacecraft's orbit. Enter a value in the scenario angle unit.
Right Ascension of Ascending Node	The angle between the X direction of the coordinate system and the point where the orbit crosses the X-Y plane in the +Z direction. Enter a value in the scenario angle unit.
Argument of Periapsis	The angle measured in the direction of spacecraft motion, in the orbit plane, from the ascending node to the periapsis of the orbit. Enter a value in the scenario angle unit.

True Anomaly	The angle from the periapsis of the orbit to the spacecraft's position vector, measured in the direction of spacecraft motion. Enter a value in the scenario angle unit.

Modified Keplerian Elements

If you select Modified Keplerian as the Element Type, the components to be specified are the same as those in the Keplerian type, with Radius of Periapsis substituted for Semimajor Axis. Radius of Periapsis is the distance from the center of mass of the central body to the periapsis of the orbit. Enter a value in the scenario distance unit (e.g. km).

Spherical Elements

If you select Spherical as the Element Type, the following six components need to be specified:

Element	Description
Right Ascension	Angle measured in the inertial equatorial plane from the inertial X axis in a right-handed sense about the inertial Z axis to the spacecraft position vector. Enter a value in the scenario angle unit.
Declination	The angle from the X-Y plane of the coordinate system to the spacecraft position vector. Enter a value in the scenario angle unit.
Radius Magnitude	The magnitude of the spacecraft position vector. Enter a value in the scenario distance unit (e.g. km).
Horizontal Flight Path Angle	The complement of the angle between the spacecraft velocity vector and the radius vector (90 deg minus the vertical flight path angle). Enter a value in the scenario angle unit.
Inertial Flight Path Azimuth	The angle in the spacecraft local horizontal plane between the projection of the velocity vector onto that plane and the local +Z direction measured as positive in the clockwise direction from north. Enter a value in the scenario angle unit.
Inertial Velocity Magnitude	The magnitude of the spacecraft velocity vector. Enter a value in the scenario distance unit per the scenario time unit (e.g. km/sec).

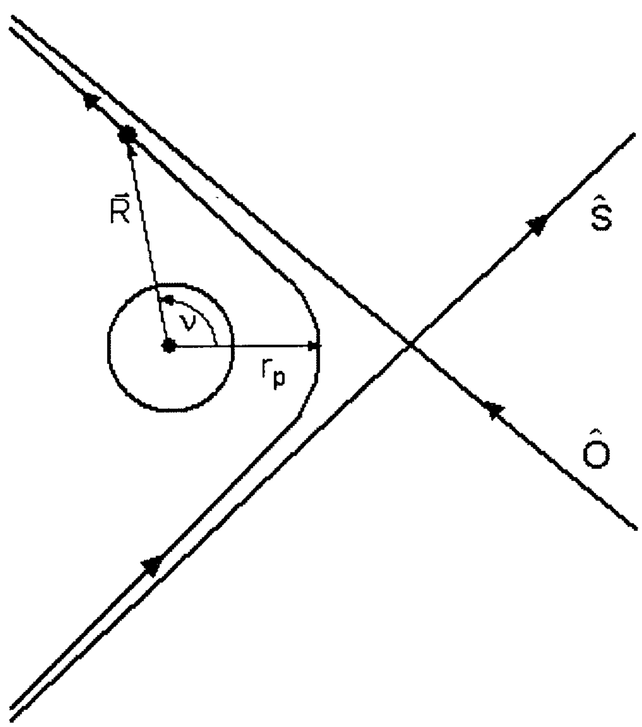
Target Vector Elements -- Incoming Asymptote

If you select Target Vector Incoming Asymptote as the Element Type, the following six components need to be specified:

Element	Description
Radius of Periapsis	Distance from the center of mass of the central body to the periapsis of the hyperbolic orbit (r_p in the illustration). Enter a value in the scenario distance unit.

C3 Energy	The energy of the orbit, computed as $-\mu/a$, where μ is the gravity constant of the central body and *a* is the semimajor axis. Enter a value in the scenario distance unit squared per scenario time unit squared.
Right Ascension of Incoming Asymptote	The right ascension of the hyperbolic incoming asymptote in the selected coordinate system. Enter a value in the scenario angle unit.
Declination of Incoming Asymptote	The declination of the incoming asymptote in the selected coordinate system. Enter a value in the scenario angle unit.
Velocity Azimuth at Periapsis	The inertial flight path azimuth of the trajectory measured at periapsis. Enter a value in the scenario angle unit.
True Anomaly	The angle from the periapsis of the orbit to the spacecraft's position vector, measured in the direction of spacecraft motion (the angle ν in the illustration). Enter a value in the scenario angle unit.

In the drawing below, $\hat{S}$ and $\hat{O}$ represent the incoming and outgoing asymptotes, respectively:



Target Vector Elements -- Outgoing Asymptote

If you select Target Vector Outgoing Asymptote as the Element Type, the components to be specified are the same as those in the the Incoming Asymptote type, except that (as you might expect) Right Ascension and Declination are defined in terms of the outgoing rather than the incoming asymptote.

Spacecraft Physical Values

In the Initial State segment, you can enter fuel tank and other spacecraft configuration properties in a window that appears when you click the Edit Spacecraft Physical Values... button. In addition, most of these properties can be modified at a later point in the space mission scenario via the Update segment.

Fuel Tank Configuration

The Fuel Tank Configuration frame of the Spacecraft Physical Values window offers the following parameters for user definition:

Parameter	Description
Tank Pressure	The fuel tank pressure. Enter a value in the scenario pressure unit (e.g. Pa).
Tank Volume	The volume of the fuel tank. Enter a value in the scenario distance unit cubed (e.g. km^3).
Tank Temperature	The temperature of the fuel tank. Enter a value in the scenario temperature unit.
Tank Density	The density of the fuel tank. Enter a value in the scenario mass unit per the scenario distance unit cubed (e.g. kg/km^3).
Fuel Mass	The mass of the spacecraft propellant. Enter a value in the scenario mass unit (e.g. kg).

Spacecraft Configuration

The Spacecraft Configuration frame of the Spacecraft Physical Values window offers the following parameters for user definition:

Parameter	Description
Dry Mass	The mass of the spacecraft exclusive of propellant. Enter a value in the scenario mass unit (e.g. kg).
Drag Area	The cross-sectional area of the spacecraft assumed perpendicular to the direction of motion, used for atmospheric drag calculations. Enter a value in the scenario distance unit squared.
Solar Radiation Pressure Area	The cross-sectional area of the spacecraft assumed perpendicular to the direction of solar radiation, used for solar radiation calculations. Enter a value in the scenario distance unit squared.
Coefficient of Drag	The dimensionless drag coefficient associated with the drag area.
Coefficient of	The reflectivity of the spacecraft used for solar radiation pressure

Reflectivity	calculations, where 2.0 is fully reflective and 1.0 is not reflective at all.

The Update Segment

All spacecraft configuration parameters except Tank Volume and Tank Density can be modified using the Update Segment. For each such parameter, the Update segment allows you to carry out the following actions:

Action	Description
Add value	Add the quantity entered in the Value column to the current value for this parameter.
Subtract value	Subtract the quantity entered in the Value column from the current value for this parameter.
Set to new value	Replace the current value for this parameter with the quantity entered in the Value column.
No change in value.	Leave the current value for this parameter unchanged (ignoring any quantity that may appear in the Value column).

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Launch Segment | Burnout Velocity

Launch & Burnout

Astrogator provides the capability of modeling a simple spacecraft launch from Earth or another central body. Launch and burnout parameters can be specified, and additional options are provided concerning burnout velocity.

This is the same capability as that of Simple Ascent. It is used for data visualization and for some launch window calculations. The user inputs the launch site coordinates, launch time, time of flight for insertion, and insertion position and velocity in ECF (Earth-centered fixed) coordinates. The launch segment calculates a simple ellipse (in ECF) to connect the launch site with the insertion position.

Typically, a launch vehicle manufacturer will supply a mission analyst with an insertion vector in the ECF frame, as well as the time of flight. Using Astrogator's Launch segment, you can then model the launch data received from the manufacturer and vary the launch time to meet other mission requirements.

Launch Segment

The Launch segment window allows you to specify the following parameters for launch and burnout:

Parameter	**Description**
Central Body	Click the ellipsis (...) button and select a central body in the window that appears.
Step Size	Enter the desired step size for the launch segment in the scenario time unit.
Launch Coordinate Type	Select between: • Geocentric (Planetocentric) -- measured from the center of mass of the Earth or other central body. • Geodetic (Planetodetic) -- measured from the surface of the Earth or other central body.
Launch Epoch	Enter the date and time of the launch in the scenario date and time format.
Launch Latitude	Enter the latitude of the launch site in the scenario angle unit.
Launch Longitude	Enter the longitude of the launch site in the scenario angle unit.
Launch Radius/Altitude	Enter the radius (planetocentric) or altitude (planetodetic) of the launch site.
	Select between:

Burnout Coordinate Type	• Geocentric (Planetocentric) -- measured from the center of mass of the Earth or other central body. • Geodetic (Planetodetic) -- measured from the surface of the Earth or other central body.
Time of Flight	Enter the time of flight (the time between launch and burnout) in the scenario time unit.
Burnout Latitude	Enter the latitude of the spacecraft at burnout in the scenario angle unit.
Burnout Longitude	Enter the longitude of the spacecraft at burnout in the scenario angle unit.
Burnout Radius/Altitude	Enter the radius (planetocentric) or altitude (planetodetic) of the spacecraft at burnout.

Burnout Velocity Options

Click the Burnout Velocity... button to bring up a window providing the following options:

Parameter	Description
Burnout Options	Select between: • Use Fixed Velocity • Use Inertial Velocity
Fixed Velocity	Fixed Velocity is the velocity relative to the rotating planet. If this option is selected, enter that value here in the scenario distance unit per scenario time unit (e.g. km/sec).
Inertial Velocity	If the Inertial Velocity option is selected, enter that value here in the scenario distance unit per scenario time unit (e.g. km/sec).
Inertial Velocity Azimuth	If the Inertial Velocity option is selected, enter the inertial velocity azimuth here in the scenario angle unit.
Inertial Horizontal Flight Path Angle	If the Inertial Velocity option is selected, enter the inertial horizontal flight path angle here in the scenario angle unit.

- The final state of the launch segment is solely and completely determined by the burnout position and velocity if the Use Inertial Velocity option is selected. If Use Fixed Velocity is selected, the inclination of the final state is determined by the arc between the launch and insertion positions, and the horizontal flight path angle is set to zero.

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Impulsive Maneuvers | Finite Maneuvers

Maneuvers

Astrogator provides two basic types of maneuvers -- impulsive and finite -- for use in constructing your space mission scenario. Both types of segments are available for building up a Mission Control Sequence in the Orbit tab of the Satellite Basic Properties window. In addition, both of these maneuver types can be used as a basis for creating new segments with the Astrogator Component Browser.

Impulsive Maneuver Segment

The Impulsive Maneuver segment models a maneuver as if it takes place instantaneously and without any change in the position of the spacecraft. This is the classic 'Delta-V' (ΔV). The final state vector is calculated by applying the specified ΔV vector to the initial velocity vector (respecting the coordinate system, of course). The Impulsive Maneuver window lets you specify the following parameters:

Parameter	Description
Thrust Axes	Click the ellipsis (...) button and select the thrust axes to be used in modeling this maneuver. These constitute the coordinate system of the ΔV vector.
Vector Type	Select between: • Cartesian -- enter values for the components displayed for the selected thrust axes (usually X, Y and Z). • Spherical -- enter values for the azimuth, elevation and magnitude of the velocity vector.
Engine Model	Click the ellipsis (...) button and select the engine model to be used in modeling this maneuver. Select whether to have the mass of the spacecraft decremented on the basis of fuel usage. The Decrement option has no effect on the ΔV itself. If selected, however, the mass of the spacecraft will be decremented by an approximated ΔM, using the rocket equation.: $\Delta V = V_e ln(m_0/m_f)$ where V_e = exhaust velocity, m_0 = initial mass and m_f = final mass, and thrust and I_{sp} are held constant to their values at the beginning of the burn. See the technical notes for the derivation of the equation relating change in mass to ΔV.

Finite Maneuver Segment

The Finite Maneuver segment takes into account changes that occur throughout the duration of

the maneuver by numerically integrating the effect of the acceleration from the engine. The Finite Maneuver window presents the following options:

Parameter	Description
Attitude Control	Select among: • Along Velocity Vector -- Attitude is such that the total thrust vector is aligned with the spacecraft's inertial velocity vector. • Anti-Velocity Vector -- Attitude is such that the total thrust vector is opposite to the spacecraft's inertial velocity vector. • Thrust Vector -- The total thrust vector can be specified in cartesian or spherical form in the thrust axes (see below).
Thrust Axes	Click the ellipsis (...) button and select the thrust axes to be used in modeling this maneuver. These constitute the coordinate system for the maneuver.
Attitude Update	Select between: • Inertial at ignition -- Specified by Attitude Control at ignition and remains the same throughout the maneuver. This fixes the thrust direction in the inertial direction calculated at the beginning of the burn and is used for inertially fixed spacecraft. • Update during burn -- Updated throughout the maneuver so as to maintain the required thrust direction. This forces the thrust vector to the specified direction at every instant throughout the burn. The thrust vector therefore rotates with the specified coordinate system (in case the Thrust Vector option is chosen) or tracks with the spacecraft's inertial velocity vector (if the Along Velocity or Anti-Velocity Vector option is chosen).
Vector Type	Select between: • Cartesian -- enter values for the components displayed for the selected thrust axes (usually X, Y and Z). • Spherical -- enter values for the azimuth, elevation and magnitude of the velocity vector. This field is active only if Thrust Vector is selected as the Attitude Control option (see above).
Stopping Conditions	Click the ellipsis (...) button to display a Propagate window, insert and/or remove one or more stopping conditions in that window and dismiss it. The Stopping Conditions frame in the Finite Maneuver window will be updated to reflect the selections made in the Propagate window. To set a trip value for a stopping condition, highlight it and enter the desired value in the Selected Condition field. Typically, the condition selected to stop the maneuver will be Duration, Epoch or Delta-V. The default Maximum Propagation Time is 7 hours.
Engine Model	Click the ellipsis (...) button and select the engine model to be used in modeling this maneuver.
	Select between: • Pressure-Regulated -- Constant pressure is maintained in the rocket

Pressure Mode	engine through some pressurization mechanism as the propellant mass decreases. • Blow-Down -- Pressure decreases as propellant is consumed and the volume occupied by the gasses consequently increases. This is based on the ideal gas law.
Thrust Efficiency	Enter the thrust efficiency value. Any number above zero is valid, with typical values around 0.98 to 1.02. A value of 1.0 means 'perfect' or 'nominal' behavior. A value of 0.98 would be termed a '2% cold' burn, while a value of 1.02 would be a '2% hot' burn. ▫ A value greater than 1.0 means the engine has performed better than expected. The Space Shuttle does this frequently, as reflected in commands such as "go for 104 percent throttle up."
Thrust efficiency affects...	Indicate whether the thrust efficiency value ... • affects acceleration calculations only • affects acceleration and mass calculations

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Orbit Propagation

Propagation of an orbit is handled by the Propagate segment, the central feature of which is a mechanism for defining one or more conditions for stopping the propagation or initiating a follow-up sequence. The Propagate window offers the following options:

Option	Description
Propagator	Click the ellipsis (...) button and select a propagator from the list that appears.
Stopping Conditions	To add a stopping condition, click the Insert... button and select one from the list that appears. To delete a stopping condition, highlight it and click the Remove button. When a stopping condition is satisfied, the propagation stops or, if a follow-up sequence has been specified for this stopping condition (see below), that sequence is executed. When more than one stopping condition is selected, propagation stops (or control passes to the follow-up sequence) as soon as one of them is satisfied. ◻ If the propagation seems to be stopping prematurely, check whether it is due to the Maximum Propagation Time setting. Also, you can run a Summary Report for the Propagate segment to find out why it has stopped.
Trip	Use this field to set the desired value for the highlighted stopping condition, i.e. the value to be achieved in order for the condition to be deemed satisfied.
Tolerance	Use this field to set the desired tolerance within which the trip value must be satisfied for the highlighted stopping condition.
Sequence	Click the ellipsis (...) to the right of this field to select an action or sequence of actions to trigger if the highlighted stopping condition is satisfied. Further sequence options can be added using the Control Sequence Browser. The Stop sequence will stop propagation in this segment and allow the next segment to run. If an alternate sequence is selected, it will be run and, when finished, the current Propagate segment will continue to run until a Stop is triggered.
Central Body/ Coordinate System	Use this field, if appropriate, to select a central body or a coordinate system for the highlighted stopping condition. For example Periapsis stops the propagation on perigee if the Earth is the central body and on periselene if the Moon is.
User Calculation Object	Use this field, if appropriate, to select a User Calculation Object for the highlighted stopping condition. For user-defined stopping conditions, use this field to specify what kind of value you want to stop on.
Criterion	This field is activated when certain stopping conditions are highlighted. Select among: • Cross Increasing -- the stopping condition is satisfied when the parameter reaches a value equal to the trip value while increasing. • Cross Decreasing -- the stopping condition is satisfied when the parameter reaches a value equal to the trip value while decreasing. • Cross Either -- the stopping condition is satisfied when either of the above situations occurs.

Repeat Count	This field is active for most stopping conditions (those capable of being satisfied more than once in the course of an orbit propagation). Specify the number of times the condition must be satisfied before the propagation ends or moves on to the designated follow-up sequence.
Constraints	Click the ellipsis (...) button and, in the selection window that appears, select a constraint for the highlighted stopping condition. This is a further condition that must be met in order for the stopping condition to be deemed satisfied.
User Comment	Enter a text string to remind you later of the reasons for the various settings you have made for this propagate segment.
Advanced...	Click this button to set one or both of the following options: • Minimum Propagation Time -- No stopping conditions are checked until the specified amount of time has elapsed. • Maximum Propagation Time (Optional) -- Setting a maximum propagation time prevents the propagation from running indefinitely if none of the stopping conditions can be satisfied.

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Targeter Setup | Editing Controls and Constraints | Targeter Profiles | Advanced Options

Targeting

The Target Sequence segment gives Astrogator the powerful capability of modeling complex space flight situations quickly and accurately by defining maneuvers and propagations in terms of the goals they are intended to achieve. The method used is a differential corrector with a singular value decomposition algorithm.

Setting up the Targeter

The Target Sequence segment has associated with it one or more nested MCS segments, such as maneuvers and propagate segments, for which control variables and constraints are defined. Setting up the targeter involves making certain selections within these nested segments and in the Target Sequence segment itself. Any segment can be nested in a target sequence, and it is not uncommon to have the entire MCS nested in a target sequence. You can also insert a target sequence within another target sequence.

Because the targeter references the nested segments by name, each segment within a target sequence should have a unique name.

Selecting Control Variables and Constraint Elements

Any element of a nested MCS segment that is available for selection as a control variable will be identified by a target icon appearing adjacent to it. To select a given element as a control variable, simply click the associated icon. Your selection will be confirmed by the appearance of a check mark over the target icon. If you change your mind click the icon again; the check mark will disappear. You can select control variables in more than one nested segment and, in each, you can select as many control variables as you wish.

Targeter constraints are defined in terms of Astrogator's extensive repertoire of Calculation Objects (to which you can add). To set constraints for a given nested MCS segment, click the Results... button appearing in the upper right corner of that segment's window. This will bring up the User-Selected Results window for that segment. Here, Calculation Objects are selected for constraint definition, but their desired values are specified in the Targeter Controls and Constraints window, described below.

Configuring the Target Sequence

The Target Sequence window presents the following options for configuration:

Option	Description
	Select among:

Action	• Run Corrected Control Values -- Run the Target Sequence using control values resulting from corrections made during previous runs. • Run Nominal Control Values -- Run the Target Sequence using the initial, uncorrected values for the control variables. • Run Targeter (Calculate New Control Values) -- Run the Target Sequence, calculating new values for the control variables in an attempt to satisfy the selected constraint.
When Targeter Converges	Select the action to be carried out if and when targeting has converged: • Run to Return and continue -- Run to the first Return segment in the sequence, then pass control to the next segment *after* this target sequence. Usually the only Return is at the end of the target sequence. • Run to Return and stop -- Run the target sequence to the first Return segment, and then stop running the MCS altogether. • Stop -- Stop the MCS as soon as the target sequence has converged.
Edit Controls and Constraints...	Click this button to bring up the Targeter Controls and Constraints window.
Add/Modify Profile List...	Click this button to bring up the Targeter Profiles window.
Clear all Corrections	Restore control variables to original, pre-correction values.
Apply all Corrections	Reset nominal values of control variables to take corrections into account, and set the corrections to zero.
Maximum Iterations	The number of complete iterations of the Target Sequence to try before stopping.
Display Popup	Select this option to have a popup window appear during targeting to report the status of the targeting effort in terms of proximity to the desired value for each constraint. Instead of closing the popup to get it out of the way, you may wish merely to reposition it. When you run the targeter again, it will use the same window.
Convergence Criteria	Select between: • Constraints within tolerance • Constraints or last variable change within tolerance (last variable change is the last increment to the control variables)
Advanced Options...	Click this button to bring up the Targeter Advanced Options window.
Log File	Select this option to have the targeter generate a log file. Accept the default filename or click the ellipsis (...) button to select a new path and filename for the log file. To review the most recently generated log file, click the View... button.
	One of two values will be displayed in this read-only field after running the targeter:

Converged on last run	• True -- targeting converged for all selected constraints. • False -- targeting failed to converge for at least one selected constraint.

Editing Controls and Constraints

This window displays information about the control variables and constraint elements you have selected for the current Targeter Profile and allows you to enter information pertinent to each.

Editing Control Variables

Each control variable you have selected is listed here, along with the following information:

- Used (?) -- If an X appears in this column, the variable is being used.
- Name -- The name of the element selected as a control variable.
- New Value -- The value of the control variable after the the last targeter run.
- Last Update -- The amount by which the value of the control variable changed during the last targeter run.
- Segment -- The MCS segment to which the element selected as a control variable belongs.

The following fields, some of which are editable, appear below the Control Variables list:

Field	Description
Use	Select this option if the control variable is to be used in this run of the targeter.
Nominal	The nominal value of the element selected as a control variable. Read-only.
Correction	The amount by which the nominal value of the control variable should be corrected to satisfy the selected constraints. Enter a first guess here if you like.
New Value	The value of the control variable after the last targeter run. Read-only.
Last Update	The amount by which the value of the control variable changed during the last targeter run. Read-only.
Tolerance	The smallest update to the control variable to be made before the targeter stops. Read-only if the convergence criterion is set to Constraints Within Tolerance.
Perturbation	Enter the value to be used in calculating numerical derivatives.
Maximum Step	Enter the maximum increment to make to the value of the control variable in any one step.
Scale	Enter a specified scale value if this option has been selected in the Targeter Advanced Options window.

Editing Constraints

Each constraint element you have selected is listed, along with the following information:

- Used (?) -- If an X appears in this column, the element is being used.
- Name -- The name of the Calculation Object used as a constraint element.
- Desired -- The desired value for this constraint element.
- Achieved -- The value achieved for this constraint element during the last targeter run.
- Segment -- The MCS segment for which this constraint has been selected.

The following fields, some of which are editable, appear below the Constraints list:

Field	Description
Use	Select this option if the constraint element is to be used in this run of the targeter.
Achieved Value	The value achieved for this constraint element in the last targeter run. Read-only.
Desired Value	Enter the desired value for this constraint element.
Difference	The difference between the achieved and desired value for this constraint element. Read-only.
Convergence Tolerance	Specify how close the targeter should come to the desired value before stopping.
Scale and Weight	Enter a specified scale value and weight if this option has been selected in the Targeter Advanced Options window.

Targeter Profiles

This window provides a means of defining and storing a number of alternative targeting profiles for use in your space mission scenario. A list of all profiles that have been defined for the current Target Sequence is displayed at the top of this window and is duplicated in the main Target Sequence window.

To create a new targeter profile, highlight an existing one and click the Duplicate button. In the fields provided, give the new profile a Name and, if desired, enter a Description. Click the Active option to make this profile active. Dismiss the Targeter Profiles window, highlight the new profile in the Target Sequence window and click the Edit Controls and Constraints... button. Then, in the Targeter Controls and Constraints window, set up the new profile as desired by editing the appropriate fields.

Advanced Options

This window provides several advanced options for configuring the targeter:

Option	Description

Clear all corrections	Select this option if you want the targeter to clear all corrections made in previous targeting runs each time it performs a new run.
Number of Homotopy Steps	This integer represents the number of steps into which the problem should be divided. The targeter will then try up to the maximum number of iterations for each homotopy step.
Scale Controls and Constraints	For each of these options, select among: • By desired value • By one (no scaling) • By specified value (enter value in Targeter Controls and Constraints window) • By tolerance This allows better numerical behavior if the controls or constraints have very different magnitudes.
Use Central Differences	Select this option to use two-sided calculation for derivatives. You may wish to try this option if you find that the targeter is not converging. This will increase the accuracy of the search (though not necessarily that of the ultimate result), but it will roughly double the amount of time consumed by the search.
Line Search	Select this option to perform a line search, and enter values for the lower and upper bounds and for the desired tolerance. Use the Max # of Steps option to specify the maximum number of functions the targeter should call before breaking off the line search and continuing. This will not necessarily help the targeter converge, but it may speed up the process by taking several steps before recalculating the numerical partial derivatives.

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Other MCS Segments

The Sequence, Return and Stop segments assist you in structuring and controlling the execution of the Mission Control Sequence:

Segment	Description
Sequence	Select one or both of the following options: • Clear Map Before Each Run -- Disable this option if, for example, you wish to compare the orbit paths in this run and the previous one. Select the option if you are more interested in removing clutter from previous runs. • Draw Trajectory as it is Calculated -- If you select this option, it is unnecessary to reset the map window at the conclusion of the MCS run to see the calculated trajectories. Disable this option to speed up run time. You can use a Sequence segment to organize MCS segments into groups.
Return	This segment simply returns control to its parent segment. For example, a Return at the conclusion of a series of segments nested in a Target Sequence returns control to the Target Sequence segment. An option is provided for allowing the targeter to bypass the Return segment. Opting to bypass during targeting allows the targeter to run segments after the Return while searching for a solution. When targeting has converged, however, the sequence will be run only to the first Return in the target sequence.
Stop	When this segment is reached, execution of the MCS halts. This is used mostly to run a partial sequence without having to wait for subsequent segments to run.

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Editing Segments | Inserting and Removing Segments | Copying and Moving Segments | Nested Segments

Editing the Mission Control Sequence

The Astrogator user interface lets you name MCS segments, assign colors to certain types of segments and insert, delete, copy and move segments in the MCS tree.

Editing Segments

To edit a segment in the MCS tree, highlight it and click the button in the MCS Toolbar (the row of buttons above the MCS tree) or right-click the mouse and select Properties from the menu that appears. A Segment Properties window appears, offering some or all of the following options, depending on the MCS segment highlighted:

Field	Description
Name	Enter a text string to identify the segment. This string will appear in the MCS tree and, consequently, should be relatively short. Internal spaces are permitted.
Description	Enter a text string to remind you later of the purpose and/or any special features of the segment.
Coordinate System	Click the ellipsis (...) button and select a coordinate system for use in a Summary report.
Color	Select a color that will show up well on the selected Map background. This option is not available for segments such as Initial State or Impulsive Maneuver that represent points in time or instantaneous actions that do not result in any drawing in the Map window.

Inserting and Removing Segments

To insert a new segment *after* a given MCS segment, highlight the latter and click the button on the MCS toolbar or right-click the mouse and select Insert After from the popup menu. To insert a new segment *before* a given MCS segment, highlight the latter, right-click the mouse and select Insert Before from the popup menu. In either case a Segment Selection window will appear, listing all available MCS segments, including any you have created in the Astrogator Browser.

- If you highlight the final Return segment of the MCS, the Insert After option is not available, and clicking the toolbar button will insert the new segment before the final Return.

To remove a segment from the MCS tree, highlight it and click the button, or right-click the mouse and select Delete from the popup menu. A dialog will appear giving you the option of confirming or cancelling your action.

Copying and Moving Segments

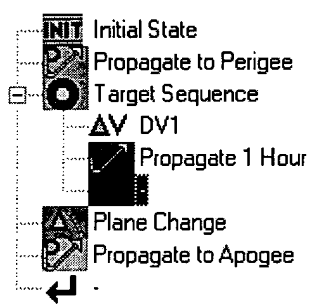
To copy a segment in the MCS tree, highlight it and click the button on the MCS toolbar, or right-click the mouse and select Copy from the popup menu. To cut a segment from the MCS tree (e.g. as a prelude to moving it elsewhere in the tree), click the button or right-click the mouse and select Cut from the popup menu.

To paste a segment *after* a given MCS segment, highlight the latter and click the button on the MCS toolbar or right-click the mouse and select Paste After from the popup menu. To paste a new segment *before* a given MCS segment, highlight the latter, right-click the mouse and select Paste Before from the popup menu.

- If you highlight the final Return segment of the MCS, the Paste After option is not available, and clicking the toolbar button will paste the new segment before the final Return.
- After cutting or copying a segment you can paste it as many times as you like in to the current MCS or into the MCS of any other satellite object in the scenario.

Nested Segments

The Sequence and Target Sequence segments introduce nested subsequences of MCS segments, such as the nested Impulsive Maneuver and Propagate segment shown here:



Like the MCS itself, a nested subsequence will end in a Return segment that cannot be deleted. When working with nested segments it is important to pay attention when selecting a destination for an Insert or Paste operation. In the MCS illustrated above, for example, if you want to insert a new segment *in the target sequence* after the nested Propagate segment ('Propagate 1 Hour'), you should highlight that segment and perform an Insert After, or highlight the nested Return segment (as shown above) and perform an Insert Before. If, instead, you highlight the unnested Finite Maneuver ('Plane Change'), the inserted segment will end up outside the nested subsequence.

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Displaying and Reporting the Mission Control Sequence

After you have designed your Mission Control Sequence, the next step is usually to run it and observe the Map window display of your spacecraft's trajectory. You can also generate detailed reports on one or more phases of the mission.

Running the MCS

To run the MCS, simply click the button, or right-click the mouse on any MCS segment and select Run Sequence from the popup menu. Depending on the MCS Options you have selected, the trajectory of your spacecraft will be drawn in the Map window as it is calculated, or you'll need to reset the Map window in order to make it appear.

- You will also need to reset the Map window if you load a saved Astrogator scenario and wish to see the Map window ephemeris before running the MCS.

If you have edited the MCS and wish to clear away old ephemeris before running the current version, click the button, or right-click the mouse on any MCS segment and select Clear from the popup menu.

MCS Summaries

To generate an MCS summary for any given phase of the mission, highlight the corresponding MCS segment and click the button, or right-click the mouse and select Summary from the popup menu. These summaries provide a wealth of data on orbital parameters and spacecraft configuration. To select a different coordinate system for the summary, highlight the appropriate segment (i.e. the one representing the phase of the mission for which a summary is desired) and edit the coordinate system in the Segment Properties window.

MCS Options

The button brings up a window providing the following options:

Option	Description
Clear Map Before Each Run	Clears all ephemeris from any previous run from the Map window before the current run draws new ephemeris.
Draw Trajectory as it is Calculated	Draws ephemeris in the Map window as it is calculated during the current run.
Propagate on Apply	Propagates trajectories if the user clicks OK or Apply in the Orbit tab. If you want to close the satellite Basic Properties window without running the MCS, make certain this option is turned OFF.

Use Trajectory Segment Colors	If selected, trajectory segments are displayed in the Map window in the colors selected for the respective Propagate segments. Otherwise, all segments are displayed in the color selected for the Satellite object.

You can also bring up this window by right-clicking the mouse on any MCS segment and selecting MCS Options from the popup menu.

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The Control Sequence Browser

The Control Sequence Browser enables you to construct follow-up sequences to be assigned to stopping conditions in Propagate and Finite Maneuver segments. To bring up the Control Sequence Browser window, click the button in the MCS toolbar.

Control Sequence Browser Window

You can add a sequence to this window by clicking the New button or by highlighting an existing sequence and clicking the Clone button to duplicate it. To remove a sequence from the list, highlight it and click the Delete button. Fields at the bottom of the window let you assign a Name to the new sequence and enter a brief Description. Click the More... button to define and/or edit the highlighted sequence.

Sequence Properties Window

This is a scaled-down version of the Mission Control Sequence window that provides the same mechanisms for inserting/removing and editing MCS segments. After you have set up the desired sequence, click OK to return to the Control Sequence Browser window.

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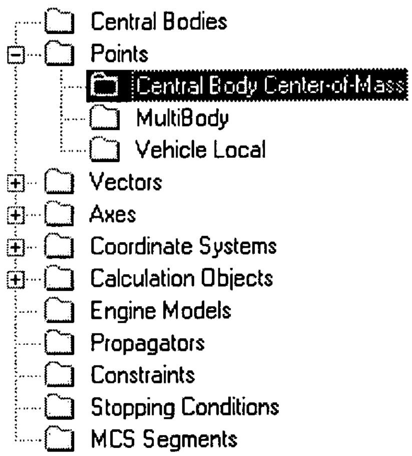
ASTROGATOR COMPONENT BROWSER



The Astrogator Component Browser is a powerful tool that enables you to redefine components of your space mission analysis and create new ones. To bring up the Component Browser, highlight the Scenario in the STK Browser window and select Astrogator Browser from the Tools menu.

The components are organized into groups listed in a tree structure in the left pane of the component browser. Individual components in a given group or subgroup are displayed in the right pane when you click the corresponding folder or subfolder in the left pane.

Click here for help on:

Central Bodies
Points
Vectors
Axes
Coordinate Systems
Calculation Objects
Engine Models
Propagators
Constraints
Stopping Conditions
MCS Segments
Creating New Components

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Graphics and Map Settings | Designing the MCS | Running the MCS

Exercise: Hohmann Transfer

The Hohmann Transfer is, in terms of the velocity change (ΔV) required, the most efficient two-burn method of transferring between two circular, coplanar orbits. As shown in the illustration, a Hohmann Transfer uses an elliptical transfer orbit with its periapsis at the inner orbit and its apoapsis at the outer orbit.

In the following exercise the purpose is to transfer a satellite from a low-Earth parking orbit with a radius of 6700 km to an outer circular orbit with a radius of 42,238 km.

- This exercise and the one that follows are based on Example 3-6-1 in Hale, Francis J., *Introduction to Space Flight*, Englewood Cliffs, N.J.: Prentice-Hall (1994), pp. 43-44.
- The values used here for the radii of the inner and outer orbits are for illustration purposes only. For further practice after completing this exercise, try substituting different values, such as a radius of 42,164.197 km (geosynchronous) for the outer orbit.

Graphics & Map Setup

The following graphics and Map window settings are recommended for this exercise:

Window	Tab	Feature	Recommended Settings
Scenario Graphics	Global Attributes	Show Orbits	ON
		Show Orbit Markers	ON
		other graphics features	OFF
Satellite Graphics	Attributes	Marker Style	X or another graphically simple style, such as Plus, Star, Circle or Square
	Pass	Orbit Lead Type	All
Map Properties	Details	Items	all geographic features OFF
		Lat/Lon Lines - Show	OFF
		Background - Image	AGI1024.bmp
		Type	Orthographic
		Displayed Coordinate Frame	ECI

		Display Height	100000 km
	Projection	Orthographic Grid - Show	ON
		Center - Lat	90 deg

Constructing the MCS

To design a Hohmann transfer from a 6700 km parking orbit to a 42,238 km outer orbit, you will use the following MCS segments:

- An Initial State defining a parking orbit with a radius of 6700 km
- A segment to Propagate the parking orbit
- An Impulsive Maneuver to enter the elliptical transfer orbit
- A segment to Propagate the transfer orbit to apogee
- An Impulsive Maneuver to enter the outer circular orbit
- A segment to Propagate the outer orbit

Let's take it a step at a time.

Define the Initial State

1. The default MCS that appears when you display the satellite's Orbit tab probably already begins with an Initial State segment. If not, insert one at the beginning of the MCS.
2. Name the segment 'Inner Orbit'.
3. Select Modified Keplerian as the Element Type and set the Radius of Periapsis to 6700 km. All other elements should be set to zero.
4. Open the Spacecraft Physical Values window and set Fuel Mass to 5000 kg.

Propagate the Parking Orbit

1. If the second segment of the MCS is not already a Propagate segment, insert one in that position.
2. Select Earth Point Mass as the Propagator.
3. If the color currently assigned to the Propagate segment won't show up well on the selected map background (or you just don't like it), select a different color.
4. Set the Duration to 2 hours (7200 sec), more than enough to have the satellite orbit one complete pass.

Maneuver into the Transfer Ellipse

1. Insert, as the third segment of the MCS, an Impulsive Maneuver.
2. Name the segment 'DV1'.
3. Select Cartesian as the Vector Type.
4. Select VNC Thrust Axes.
5. Set the X (Velocity) component to 2.421 km/sec. This will apply all the ΔV in the thrust direction.
6. Turn ON the Decrement Mass Based on Fuel Usage option.

Propagate the Transfer Orbit to Apogee

1. Insert, as the fourth segment of the MCS, another Propagate segment.
2. Name the segment 'Transfer Ellipse' and select a color that will distinguish it from the first Propagate segment.
3. Select Earth Point Mass as the Propagator.
4. Select Apoapsis as the Stopping Condition.

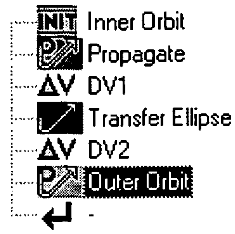
Maneuver into the Outer Orbit

1. Insert, as the fifth segment of the MCS, another Impulsive Maneuver.
2. Name the segment 'DV2'.
3. Select Cartesian as the Vector Type.
4. Select VNC Thrust Axes.
5. Set the X (Velocity) component to 1.465 km/sec.
6. Turn ON the Decrement Mass Based on Fuel Usage option.

Propagate the Outer Orbit

1. Insert, as the final segment of the MCS, a Propagate segment.
2. Name the segment 'Outer Orbit' and select a color that will distinguish it from the other two Propagate segments.
3. Select Earth Point Mass as the Propagator.
4. Set the Duration to 24 hours (86400 sec), so that the satellite will make a complete orbit pass (and one will be drawn in the Map window).

The MCS tree should appear as follows when you are finished:



Running and Analyzing the MCS

Run the MCS. The Map window display should be similar to the illustration (except that the inner orbit is closer to the central body). The parking orbit, transfer trajectory and outer orbit should be clearly differentiated by the colors you selected for the three Propagate segments.

If you highlight the last Propagate segment ('Outer Orbit') and create a Summary report, you'll find that the semimajor axis of the outer orbit is very, very close to the desired value of 42,238 km. Also check the final Fuel Mass. As you'll recall, in defining the Initial State, you set Fuel Mass to 5000 kg, and, in setting up the two Impulsive Maneuvers, you opted to have mass decremented on the basis of fuel usage. If you highlight the second Propagate segment (after the first ΔV but before the second), you'll find a value for Fuel Mass between the initial and final values.

- SUGGESTION: Save the scenario to compare the results of this exercise with those of the Fast Transfer exercise.

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Exercise: Hohmann Transfer Using the Targeter

If you did the other Hohmann Transfer exercise, you entered pre-calculated values for the two required ΔVs. In this exercise, you will let Astrogator do the work of calculating the ΔVs, using its targeting capability.

Here, as in the other exercise, the purpose is to transfer a satellite from a low-Earth parking orbit with a radius of 6700 km to an outer circular orbit with a radius of 42,238 km.

- This exercise and the preceding one are based on Example 3-6-1 in Hale, Francis J., *Introduction to Space Flight*, Englewood Cliffs, N.J.: Prentice-Hall (1994), pp. 43-44.
- The values used here for the radii of the inner and outer orbits are for illustration purposes only. For further practice after completing this exercise, try substituting different values, such as a radius of 42,164.197 km (geosynchronous) for the outer orbit.

Graphics & Map Setup

The following graphics and Map window settings are recommended for this exercise:

Window	Tab	Feature	Recommended Settings
Scenario Graphics	Global Attributes	Show Orbits	ON
		Show Orbit Markers	ON
		other graphics features	OFF
Satellite Graphics	Attributes	Marker Style	X or another graphically simple style, such as Plus, Star, Circle or Square
	Pass	Orbit Lead Type	All
Map Properties	Details	Items	all geographic features OFF
		Lat/Lon Lines - Show	OFF
		Background - Image	AGI1024.bmp
	Projection	Type	Orthographic
		Displayed Coordinate Frame	ECI
		Display Height	100000 km

		Orthographic Grid - Show	ON
		Center - Lat	90 deg

Constructing the MCS

To design a Hohmann transfer from a 6700 km parking orbit to a 42,238 km outer orbit, you will use the following MCS segments:

- An Initial State defining a parking orbit with a radius of 6700 km
- A segment to Propagate the parking orbit
- A Target Sequence containing an Impulsive Maneuver to enter the elliptical transfer orbit
- A segment to Propagate the transfer orbit to apogee
- A Target Sequence containing an Impulsive Maneuver to enter the outer circular orbit
- A segment to Propagate the outer orbit

Here it is step by step.

Define the Initial State

1. The default MCS that appears when you display the satellite's Orbit tab probably already begins with an Initial State segment. If not, insert one at the beginning of the MCS.
2. Name the segment 'Inner Orbit'.
3. Select Modified Keplerian as the Element Type and set the Radius of Periapsis to 6700 km. All other elements should be set to zero.

Propagate the Parking Orbit

1. If the second segment of the MCS is not already a Propagate segment, insert one in that position.
2. Select Earth Point Mass as the Propagator.
3. If you wish, select a different color for the segment.
4. Set the Duration to 2 hours (7200 sec), more than enough to have the satellite orbit one complete pass.

Maneuver into the Transfer Ellipse

Now use the targeter to calculate the ΔV required to move the spacecraft from the parking orbit into the transfer orbit. The goal of the targeter will be defined in terms of the radius of apoapsis of the transfer ellipse, coinciding with the radius of the desired final orbit.

Define a Target Sequence

1. Insert a Target Sequence segment.
2. Name the Target Sequence segment 'Start Transfer'.
3. Nest an Impulsive Maneuver in the Target Sequence.
4. Name the nested Impulsive Maneuver segment 'DV1'.

Select a Control Variable and Constraint Element

1. Highlight the nested Impulsive Maneuver and Select Cartesian as the Vector Type.
2. Select VNC Thrust Axes.
3. Select the X (Velocity) component as the sole control variable.
4. Select Radius of Apoapsis as the only constraint element

Set up the Targeter

1. With the Target Sequence highlighted, open the Targeter Controls and Constraints window.
2. Set the Desired value for Radius of Apoapsis to 42238 km.
3. Set the Convergence Tolerance to 0.1 and the Maximum Step to 0.3 km/sec, and close the window.
4. Increase the Maximum Iterations amount to 50 and select the Display Popup option.
5. Make sure the targeter is turned on (select Run Targeter in the Action field).

Propagate the Transfer Orbit to Apogee

1. Insert another Propagate segment.
2. Name the segment 'Transfer Ellipse'.
3. Select Earth Point Mass as the Propagator.
4. Select Apoapsis as the Stopping Condition.

Maneuver into the Outer Orbit

Here you will use the targeter to calculate the ΔV required to move the spacecraft from the transfer orbit into the circular outer orbit. With the desired radius already achieved, the goal will be to circularize the orbit, i.e., change its eccentricity to zero.

Define a Target Sequence

1. Insert another Target Sequence segment.
2. Name the Target Sequence segment 'Finish Transfer'.
3. Nest an Impulsive Maneuver in the Target Sequence.
4. Name the nested Impulsive Maneuver segment 'DV2'.

Select a Control Variable and Constraint Element

1. Highlight the nested Impulsive Maneuver ('DV2') and Select Cartesian as the Vector Type.
2. Select VNC Thrust Axes.
3. Select the X (Velocity) component as the sole control variable.
4. Select Eccentricity as the only constraint element.

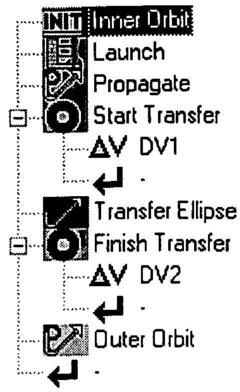
Set up the Targeter

1. With the Target Sequence highlighted, open the Targeter Controls and Constraints window.
2. Leave the Desired value for Eccentricity at its default value of zero.
3. Set the Maximum Step to 0.3 km/sec and close the window.
4. Select the Display Popup option and make sure the targeter is turned on (select Run Targeter in the Action field).

Propagate the Outer Orbit

1. Insert a Propagate segment.
2. Name the segment 'Outer Orbit'.
3. Select Earth Point Mass as the Propagator.
4. Set the Duration to 24 hours (86400 sec), so that the satellite will make a complete orbit pass (and one will be drawn in the Map window).

The MCS tree should appear as follows when you are finished:



Running and Analyzing the MCS

Run the MCS and observe the targeting process as displayed in the Popup window. When the process is finished, the Map window display should be similar to the illustration. Highlight each Target Sequence segment and open its Targeter Controls and Constraints window. You'll see that the New Values calculated for the Control Variables are very nearly the same as the calculated amounts.

- SUGGESTION: Save the scenario to compare the results of this exercise with those of the Fast Transfer exercise.

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Exercise: Fast Transfer (Using Targeter)

Here, as in the Hohmann Transfer and targeting exercises, the purpose is to transfer a satellite from a low-Earth parking orbit with a radius of 6700 km to an outer circular orbit with a radius of 42,238 km.

While a Hohmann Transfer is the most efficient two-burn maneuver to use in this situation, it is also one of the slowest. Among other things, the satellite is required to travel the entire length of the elliptical transfer orbit, including the approach to apoapsis, where its velocity is considerably slower than in the portion of the orbit near periapsis. If it is of great importance to reduce the time of flight (e.g. for a rendezvous or a planetary intercept) a maneuver such as that shown in the illustration can be used. This maneuver, known as a fast transfer, is considerably faster than a Hohmann Transfer, but, of course, it uses more fuel.

- This exercise is based on Example 3-6-5 in Hale, Francis J., *Introduction to Space Flight*, Englewood Cliffs, N.J.: Prentice-Hall (1994), pp. 48-50.
- The values used here for the radii of the inner and outer orbits are for illustration purposes only. For further practice after completing this exercise, try substituting different values, such as a radius of 42,164.197 km (geosynchronous) for the outer orbit.

Graphics & Map Setup

The following graphics and Map window settings are recommended for this exercise:

Window	Tab	Feature	Recommended Settings
Scenario Graphics	Global Attributes	Show Orbits	ON
		Show Orbit Markers	ON
		other graphics features	OFF
Satellite Graphics	Attributes	Marker Style	X or another graphically simple style, such as Plus, Star, Circle or Square
	Pass	Orbit Lead Type	All
Map	Details	Items	all geographic features OFF
		Lat/Lon Lines - Show	OFF
		Background - Image	AGI1024.bmp
		Type	Orthographic

Properties	Projection	Displayed Coordinate Frame	ECI
		Display Height	100000 km
		Orthographic Grid - Show	ON
		Center - Lat	90 deg

Constructing the MCS

To design a fast transfer from a 6700 km parking orbit to a 42,238 km outer orbit, you will use the following MCS segments:

- An Initial State defining a parking orbit with a radius of 6700 km
- A segment to Propagate the parking orbit
- A Target Sequence containing an Impulsive Maneuver to enter a large elliptical transfer orbit (aiming at twice the desired radius of apoapsis)
- A segment to Propagate the transfer orbit halfway to apoapsis
- A Target Sequence containing an Impulsive Maneuver to cut short the transfer trajectory and enter the outer circular orbit (the fast transfer)
- A segment to Propagate the outer orbit

We're good to go.

Define the Initial State

1. The default MCS that appears when you display the satellite's Orbit tab probably already begins with an Initial State segment. If not, insert one at the beginning of the MCS.
2. Name the segment 'Inner Orbit'.
3. Select Modified Keplerian as the Element Type and set the Radius of Periapsis to 6700 km. All other elements should be set to zero.
4. Open the Spacecraft Physical Values window and set Fuel Mass to 5000 kg.

Propagate the Parking Orbit

1. If the second segment of the MCS is not already a Propagate segment, insert one in that position.
2. Select Earth Point Mass as the Propagator.
3. If you wish, select a different color for the segment.
4. Set the Duration to 2 hours (7200 sec), more than enough to have the satellite orbit one complete pass.

Maneuver into the Transfer Ellipse

Now use the targeter to calculate the Δ V required to move the spacecraft from the parking orbit into the transfer orbit. The goal of the targeter will be defined in terms of the radius of apoapsis of the transfer ellipse, twice the radius of the desired final orbit.

Define a Target Sequence

1. Insert a Target Sequence segment.
2. Name the Target Sequence segment 'Start Transfer'.
3. Nest an Impulsive Maneuver in the Target Sequence.
4. Name the nested Impulsive Maneuver segment 'DV1'.

Select a Control Variable and Constraint Element

1. Highlight the nested Impulsive Maneuver and Select Cartesian as the Vector Type.
2. Select VNC Thrust Axes.
3. Select the X (Velocity) component as the sole control variable.
4. Select Radius of Apoapsis as the only constraint element
5. Turn ON the Decrement Mass Based on Fuel Usage option.

Set up the Targeter

1. With the Target Sequence highlighted, open the Targeter Controls and Constraints window.
2. Set the Desired Value for Radius of Apoapsis to 88176 km.
3. Set the convergence tolerance to 0.1 and close the window.
4. Increase the Maximum Iterations amount to 50 and select the Display Popup option.
5. Make sure the targeter is turned on (select Run Targeter in the Action field).

Propagate the Transfer Orbit to 42,238 km

1. Insert another Propagate segment.
2. Name the segment 'Transfer Ellipse' and select a color that will distinguish it from the first Propagate segment.
3. Select Earth Point Mass as the Propagator.

4. Select R Magnitude as the Stopping Condition and set the trip value to 42238 km.

Maneuver into the Outer Orbit

Here you will use the targeter to calculate the ΔV required to break out of the transfer orbit midway to apogee and enter the outer circular orbit. The goal will be to circularize the orbit, i.e., change its eccentricity to zero.

Define a Target Sequence

1. Insert another Target Sequence segment.
2. Name the Target Sequence segment 'Finish Transfer'.
3. Nest an Impulsive Maneuver in the Target Sequence.
4. Name the nested Impulsive Maneuver segment 'DV2'.

Select Control Variables and Constraint Elements

1. Highlight the nested Impulsive Maneuver ('DV2') and Select Cartesian as the Vector Type.
2. Select VNC Thrust Axes.
3. Select the X (Velocity) and Z (Co-Normal) components as the control variables.
4. Select Eccentricity and Horizontal Flight Path Angle as constraint elements.
5. Turn ON the Decrement Mass Based on Fuel Usage option.

Set up the Targeter

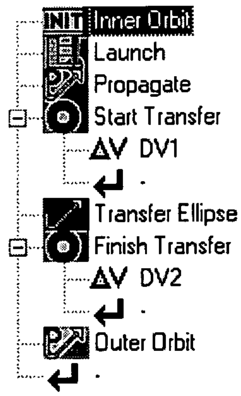
1. With the Target Sequence highlighted, open the Targeter Controls and Constraints window.
2. Leave the Desired Values for Eccentricity and Horizontal Flight Path Angle at their default values of zero.
3. Set the Maximum Step for each of the control variables at 0.3 km/sec and close the window.
4. Increase the Maximum Iterations amount to 50 and select the Display Popup option.
5. Make sure the targeter is turned on (select Run Targeter in the Action field).

Propagate the Outer Orbit

1. Insert a Propagate segment.

2. Name the segment 'Outer Orbit' and select a color that will distinguish it from the other two Propagate segments.
3. Select Earth Point Mass as the Propagator.
4. Set the Duration to 24 hours (86400 sec), so that the satellite will make a complete orbit pass (and one will be drawn in the Map window).

The MCS tree should appear as follows when you are finished:



Running and Analyzing the MCS

Run the MCS and observe the targeting process as displayed in the Popup window. When the process is finished, the Map window should show a sharp turn from the transfer trajectory into the final orbit, similar to that shown in the illustration. Because of the change in direction, it is necessary to select two components of the second Δ V as control variables.

Highlight the second Target Sequence segment, open the Targeter Controls and Constraints window and note the New Values for the Control Variables. Using these values to compute the value of ΔV_2,

$$\Delta V_2 = \sqrt{(-1.652)^2 + (-2.632)^2} = 3.107 \text{ km / sec}$$

yields a result that is very close to that reached via the Law of Cosines.

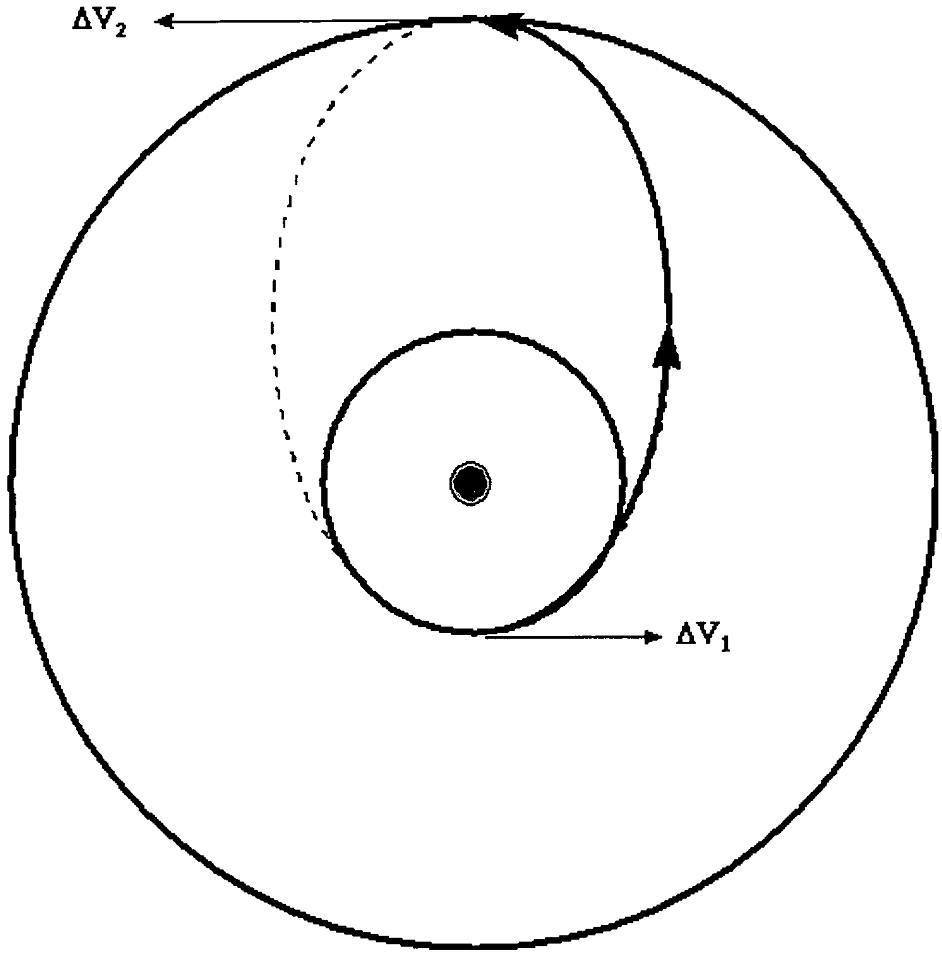
- The New Values you observe may differ slightly from those shown here, depending, e.g., on the Convergence Tolerance you use for Eccentricity in the second Target Sequence.

Why are the correction values negative? Because you are transferring into a lower energy orbit and slowing down.

As the technical notes for this exercise show, a fast transfer is more expensive in terms of Δ V, but takes considerably less time, than a Hohmann transfer. You can also confirm this by running a Summary for the final Propagate segment and comparing the final Fuel Mass value with that for the Hohmann Transfer exercise.

Exercise: Hohmann Transfer -- Technical Notes

Illustration of a Hohmann Transfer



Since the ΔVs occur at the apsides, the horizontal flight path angle is zero at the time of each burn and the velocity vector of the transfer orbit at each apside is collinear with that of the respective circular orbit. Thus, in the case of a Hohmann Transfer between inner and outer orbits, ΔV_1 is the additional thrust needed to increase the apoapsis of the orbit to the radius of the outer circle, and ΔV_2 is the further thrust needed to circularize the orbit, i.e., to increase its periapsis to be equal to its apoapsis.

- These notes are based on Example 3-6-1 in Hale, Francis J., *Introduction to Space Flight*, Englewood Cliffs, N.J.: Prentice-Hall (1994), pp. 43-44.

Derivation of Values Used for Delta-Vs

To compute the ΔVs for the Hohmann Transfer, you need to know the velocity of the satellite in each of the circular orbits and at the apsides of the transfer ellipse. The velocities of the inner and outer orbits are given by:

$V_i = \sqrt{\frac{\mu}{r_i}}$ = 7.713 km/sec $\qquad$ $V_o = \sqrt{\frac{\mu}{r_o}}$ = 3.072 km/sec

where μ is the Earth's gravitational parameter and r_i and r_o are the radii of the respective orbits. The energy of the transfer orbit is given by

$$\mathcal{E} = \frac{-\mu}{r_i + r_o} = -8.145$$

Using the well-known vis viva equation and solving for velocity,

$$V = \sqrt{2\left(\mathcal{E} + \frac{\mu}{r}\right)} = -8.145$$

where $r = r_i$ at perigee and $r = r_o$ at apogee, the velocities at the apsides are

V_{t_p} = 10.134 km/sec $\qquad$ V_{t_a} = 1.607 km/sec

Thus,

$\Delta V_1 = V_{t_p} - V_i$ = 2.421 km/sec $\qquad$ $\Delta V_2 = V_o - V_{t_a}$ = 1.465 km/sec

The total velocity change required for the transfer is

$$\Delta V = \Delta V_1 + \Delta V_2 = 3.886 \text{ km/sec}$$

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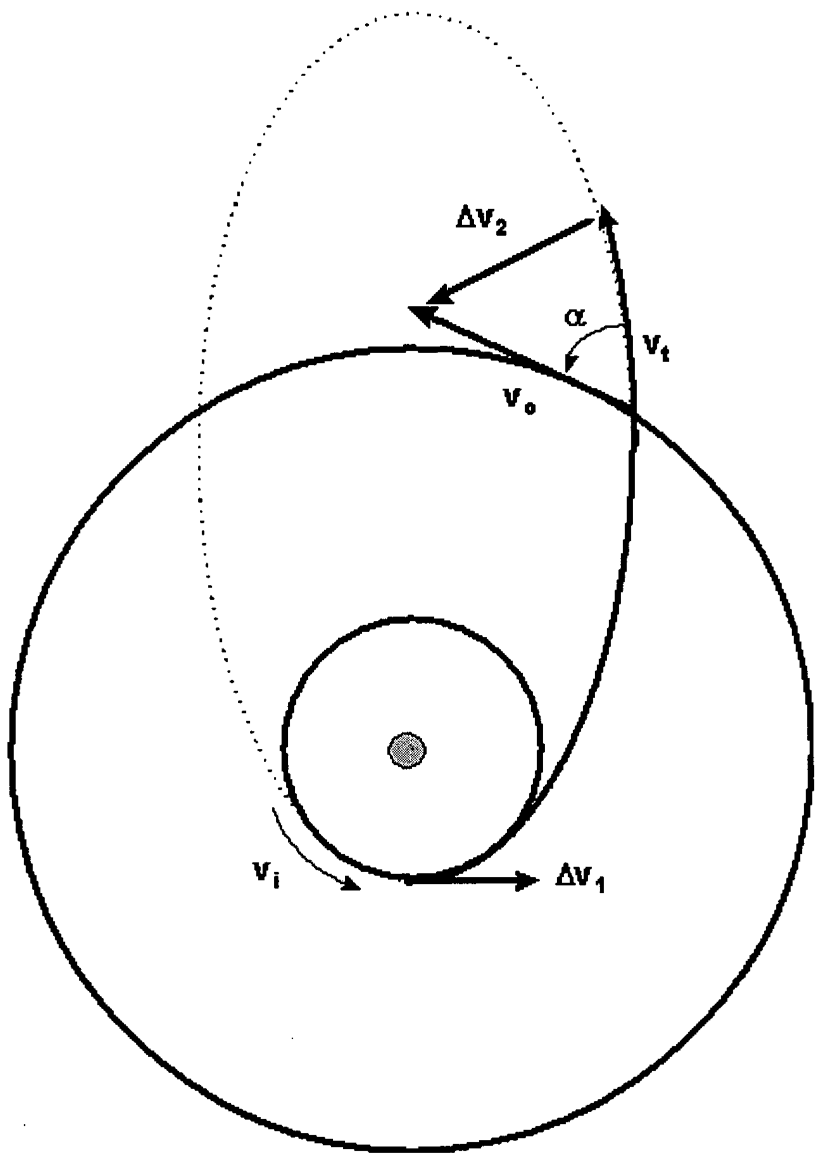
Exercise: Fast Transfer -- Technical Notes

Illustration of a Fast Transfer



In the Fast Transfer shown here, ΔV_1 is, as in the case of a Hohmann Transfer, carried out at periapsis of the transfer trajectory. However, the radius of apoapsis of the transfer orbit is greater than the radius of the outer circular orbit, and, instead of proceeding to apoapsis, the journey of the satellite is interrupted by a second burn when it reaches the desired final radius. It can be seen that ΔV_2 changes not only the magnitude of the velocity vector but also its direction.

- This discussion and the related exercise are based on Example 3-6-5 in Hale, Francis J., *Introduction to Space Flight*, Englewood Cliffs, N.J.: Prentice-Hall (1994), pp. 48-50.

Derivation of Values Used for Delta-Vs

The amount of ΔV needed can be calculated using the Law of Cosines, where V_o is the velocity of the outer orbit, V_t is the velocity of the transfer orbit where it intersects the outer orbit, and α is the angle between $\vec{V}_o$ and $\vec{V}_t$

$$\Delta V_2 = \sqrt{V_o^2 + V_t^2 - 2V_o V_t \cos\alpha}$$

The transfer trajectory can be a parabola or hyperbola instead of an ellipse, but an ellipse is the usual choice.

For the Fast Transfer you are using a transfer ellipse with a semimajor axis twice as large as that of the one you used in the Hohmann Transfer, which was 42,238 km. The energy of the transfer orbit is

$$\mathcal{E} = \frac{-\mu}{2a} = -4.072 \times 10^6 \text{ m}^2/\text{sec}^2$$

where *a* is the semimajor axis. The velocities at periapsis of the transfer trajectory and at the point where it intersects the outer orbit are, respectively,

$$V_{t_p} = \sqrt{2\left(\mathcal{E} + \frac{\mu}{r_i}\right)} = 10.528 \text{ km/sec} \qquad V_{t_o} = \sqrt{2\left(\mathcal{E} + \frac{\mu}{r_o}\right)} = 3.276 \text{ km/sec}$$

Recalling that V_i = 7.713 km/sec, you can calculate ΔV_1 in the same manner as for the Hohmann Transfer:

$$\Delta V_1 = V_{t_p} - V_i = 2.814 \text{ km/sec}$$

- Notice that ΔV_1 is greater here than in the Hohmann Transfer, since the Fast Transfer ellipse has a greater semimajor axis and, consequently, a greater specific mechanical energy than the Hohmann ellipse.

Before you can apply the Law of Cosines to compute ΔV_2, you need to know the angle α between the velocity vector of the spacecraft in the transfer orbit and its velocity vector after transferring to the outer circular orbit (see illustration). It will help here (and in calculating time of flight) to know the eccentricity of the Fast Transfer ellipse and the true anomaly of the spacecraft's position at the intersection between the transfer trajectory and the outer circular orbit.

Since you know the radius of periapsis and semimajor axis of the transfer ellipse, you can derive its eccentricity from the relationship $r_p = a(1 - e)$:

$$e = 1 - \frac{r_p}{a} = 0.8631$$

The ellipse's semilatus rectum is given by

$$p = a(1 - e^2) = 12{,}482 \text{ km}$$

With *e* and *p*, you can determine the true anomaly at r_o:

$$\nu_o = \cos^{-1}\left[\frac{1}{e}\left(\frac{p}{r_o} - 1\right)\right] = 144.7 \text{ deg}$$

The angle between the two velocity vectors is

$$\alpha = \tan^{-1}\left(\frac{e \sin \nu_o}{1 + e \cos \nu_o}\right) = 59.35 \text{ deg}$$

Thus,

$$\Delta V_2 = \sqrt{V_{t_o}^2 + V_o^2 - 2V_{t_o} V_o \cos\alpha} = 3.148 \text{ km/sec}$$

and the total ΔV needed for the Fast Transfer is

$$\Delta V = \Delta V_1 + \Delta V_2 = 5.962 \text{ km/sec}$$

which is more than 50 % greater than that needed for the Hohmann Transfer.

Hohmann and Fast Transfer Compared (TOF)

As you have seen, the Fast Transfer is more than 50% more expensive than a Hohmann Transfer that achieves the same result. However, it is also nearly twice as fast.

Since the Hohmann transfer begins at periapsis and ends at apoapsis of the transfer ellipse, the time of flight (TOF) is just half the period of the ellipse, i.e.

$$\text{TOF} = \pi\sqrt{\frac{a^3}{\mu}} = 19{,}046 \text{ seconds} = 5.29 \text{ hours}$$

For the Fast Transfer, first calculate eccentric anomaly (*E*):

$$E = \cos^{-1}\left(\frac{e + \cos\nu}{1 + e\cos\nu}\right) = 80.9° = 1.411 \text{ rad}$$

Then apply Kepler's Equation to derive mean anomaly (*M*):

$$M = E - e \sin E = 0.559 \text{ rad}$$

Finally, use the mean anomaly value to calculate TOF:

$$TOF = \left(\sqrt{\frac{a^3}{\mu}}\right)M = 9585 \text{ seconds} = 2.66 \text{ hours}$$

Again, the greater speed of the Fast Transfer is not surprising, given the fact that it occurs about halfway between perigee and apogee of the transfer ellipse and does not include the significant slowing down that occurs when an orbiting body approaches apoapsis.

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The Differential Corrector

The basic targeting problem can be summarized as follows. Given a specified set of orbital goals, how can the initial conditions and intermediate variables be perturbed to meet those goals. A robust mechanism used by Astrogator for solving this problem is the differential corrector.

The differential corrector in Astrogator works by expressing the targeting problem in terms of a pseudo-Taylor series expansion of the goals *G* expressed as a function of the variables *v*. The problem can be represented by the expression

Equation 1

$$G_1(v_1) = \vec{G}(\vec{r},\vec{v},t) = G_0 + \left[\sum_{n=1}^{\infty} \frac{1}{n!} \frac{d^n G}{dv^n}\bigg|_{v=v_0} (v_1 - v_0)^n\right],$$

where the term in brackets is the Taylor series expansion of the equation for the goals *G(v)* expanded in terms of the variables *v*. Since the problem as stated involves a complicated combination of gravitating bodies and additional forces, there is no closed-form expression for *G*, and the Taylor series expansion cannot be performed analytically. In addition, even if a formula for *G* were available, the series expansion is in principle infinite and therefore impossible to solve exactly except in special cases.

An alternative approach is to truncate the Taylor series expansion (Equation 3) at a convenient point and evaluate the resulting equation numerically. When the series is truncated at the first derivative, the following equation remains:

Equation 2

$$G_1(v_1) \approx G_0 + \frac{dG}{dv}(v_1 - v_0)$$

This equation can be rearranged to give:

Equation 3

$$G_1' = \frac{dG}{dv} \approx \frac{G_1 - G_0}{v_1 - v_0} \quad \rightarrow \quad v_1 \approx v_0 + \frac{G_T - G_0}{G_1'} = v_0 + (G_T - G_0)\left[G_1'\right]^{-1}$$

Thus, we can find the value of v_1 that approximates the value of the variables needed to meet our goal G_T if we know the initial value for the variable v_0 and can find an approximation to the derivative G_1'. To generate this approximation, we need only perturb each variable by some small amount δv and measure the resulting change in each goal *G*. Then, by the fundamental theorem of calculus,

Equation 4

$$G_1' = \frac{dG}{dv} = \lim_{\delta v \to 0} \frac{G(v + \delta v) - G(v)}{\delta v}$$

The limit cannot be taken to zero numerically because of the finite precision of your computer. When you target a goal in Astrogator, you can enter the value of the perturbation (*v* in this case) in the Perturbation field for the appropriate variable in the targeter, or you can let Astrogator use a default value. The targeter then proceeds to run a nominal trajectory to calculate the starting value of the parameter describing the goal you set. Then it adds the perturbation to the variable and performs the targeting sequence. This information is used in Equation 4 to calculate an approximate local value for the first derivative of the equation describing your goal. This value is then used in Equation 3 to determine a new estimate for the variable used in the targeter. This process is then repeated until the achieved value of the goal falls within the (user-specified) tolerance for the goal.

Several complications arise when the problem being solved contains more than one variable and goal. You may have noted that Equation 3 contains the inverse of the derivative operator. When the problem being solved contains two variables (say, *x* and *y*) and two goals (*A* and *B*), there are two equations that describe the solution:

Equations 5

$$f(x + \Delta x, y + \Delta y) = A$$
$$g(x + \Delta x, y + \Delta y) = B$$

Here *f(x,y)* is the equation describing the goal that has a targeted value of *A*, and *g(x,y)* is the equation describing the goal with a targeted value of *B*. Each of these equations is evaluated with the perturbation of each variable separately. The resulting matrix equation has the following form:

Equation 6

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \approx \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \end{bmatrix}^{-1} \begin{bmatrix} A - f(x,y) \\ B - g(x,y) \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} + \left[\tilde{M}' \right]^{-1} \begin{bmatrix} A - f(x,y) \\ B - g(x,y) \end{bmatrix}$$

The matrix $\left[\tilde{M}' \right]^{-1}$ of the partial derivatives is called the 'sensitivity matrix.' This matrix must be invertible for the differential corrector to perform correctly; among other things, this means that there must be no degeneracy in the matrix. Astrogator uses a singular value decomposition (SVD) algorithm to invert this matrix.

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Calculation Objects

Astrogator makes a number of Calculation Objects available for use in constructing other components, such as stopping conditions, or for use as results, targeter constraints and report and graph elements. Also, you can create new Calculation Objects using the Astrogator Component Browser. The types of Calculation Objects provided with Astrogator include the following:

Type	Description
Epoch	The epoch of a given state in the Mission Control Sequence.
Cartesian Elements	X, Y and Z components of position and velocity vectors.
Geostationary	Longitude drift rate in angle/time, positive toward East.
Geodetic	Latitude, longitude, altitude.
Keplerian Elements	Classical elements specifying an orbit by its size, shape and three-dimensional orientation in space.
Maneuver	Δ V integrated along orbit path.
Math	Absolute value and negative.
Multibody	B-plane elements, delta declination and right ascension.
Other Orbit	Including beta angle, C3 energy, true longitude, etc.
Spherical Elements	Azimuth, right ascension, declination, flight path angle, R magnitude, etc.
Time	Duration from a given epoch.
Vector	Vector components, dot products, angles between vectors, etc.

A brief description of a Calculation Object is displayed when you highlight it in the Astrogator Component Browser. To view the elements of a Calculation Object (and edit them, if the variable is a copy), double click it in the Component Browser, bringing up its Component Edit window.

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